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Conjugate heat transfer analysis of the effects of impingement channel height for a turbine blade endwall

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ABSTRACT

Advancements in cooling for applications such as gas turbines components require improved understanding of the complex heat transfer mechanisms and the interactions between those mechanisms. Critical cooling applications often rely on multiple thermal protection techniques, including internal cooling and external film cooling in gas turbine airfoils, to efficiently cool components and limit the use of coolant. Most research to quantify the effectiveness of such cooling technologies for gas turbine applications has isolated internal and external cooling in separate experiments. The research presented in this paper uses a conjugate heat transfer approach to account for the combined effects of both internal and external cooling. The geometry used for this study is a turbine blade endwall that includes impingement and film cooling as well as the relevant conduction through the endwall. Appropriate geometric and flow parameters were scaled to ensure engine relevant dimensionless temperatures were obtained. Using the conjugate heat transfer approach, the effect of varying the height of the impingement channel was examined using spatially resolved external wall temperatures obtained from both experiments and simulations. A one-dimensional heat transfer analysis was used to derive the average internal heat transfer coefficients from the experimental results. Both experiments and simulations showed good agreement between area averaged cooling effectiveness and impingement heat transfer coefficients. The cooling effectiveness and heat transfer coefficients peaked for an impingement channel height of around three impingement hole diameters. However, the heat transfer coefficients were more sensitive than the overall effectiveness to the changes in height of the impingement channel.

1. Introduction

A continuing challenge in advanced cooling applications is understanding the interaction between multiple heat transfer mechanisms, which is referred to as conjugate heat transfer. Conjugate heat transfer is the combined result from convective heating and cooling, conduction within the walls, and radiation heat transfer. In many applications such as along gas turbine components, the most effective cooling configurations are often three-dimensional and are surrounded by complicated flow fields and thermal fields. In a gas turbine engine, the airfoil and endwall surfaces simultaneously experience convective heating from the hot combustion gases and convective cooling from air supplied by the compressor that has bypassed the combustor. The convective cooling occurs both internal to the airfoil, such as through jet impingement, and external to the airfoil, such as through small angled holes in the airfoil walls providing what is known as film cooling. In combined impingement and film cooling, the cooling air impinges on the internal walls, and then passes through the film cooling holes to generate a protective film of coolant on the outer wall. The combination of the convective and conductive heat transfer processes determines the resulting wall temperature, which governs the service life of the turbine components. Therefore, accurate predictions of component temperature are critical to evaluate cooling technologies.

Current practices to predict turbine component temperatures involve calculating the solid conduction using analytical or numerical tools while applying convective boundary conditions based on separate internal and external experiments or analyses. Most literature in gas turbine heat transfer reports either heat transfer coefficients measured with a constant heat flux boundary condition or adiabatic film cooling effectiveness measured with an adiabatic boundary condition. The latter is applied in analytical or numerical tools to represent the reference temperature for external convection in the presence of film cooling. An alternative to this isolated heat transfer analysis is direct determination of the non-dimensional wall temperature, referred to as the overall

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Nomenclature

A	area
Bi	Biot number ($h_\infty t/k_w$)
C_{ax}	axial chord length
C_d	discharge coefficient
c_p	specific heat
D	hole diameter
DR	density ratio (ρ_c/ρ_∞)
H	impingement gap height
h	convective heat transfer coefficient
k	thermal conductivity
L	length
M	blowing ratio ($\rho_c U_c/\rho_\infty U_\infty$)
Ma	Mach number
$\dot{m}$	mass flow rate
$Nu_{D,i}$	internal Nusselt number ($h_i D/k_{c,in}$)
P	pressure
p	pitch length
q	heat flux
Re	mainstream Reynolds number ($\rho_\infty U_\infty C_{ax}/\mu_\infty$)
Re_D	impingement Reynolds number ($\rho_{c,in} U_c D/\mu_{c,in}$)
S	blade span
T	temperature
t	thickness
U	streamwise velocity
u'	fluctuating velocity
x, y, z	global coordinates, where x is blade axial direction

Greek

δ	boundary layer thickness
μ	dynamic viscosity
ρ	density
ϕ	overall effectiveness $(T_\infty - T_w)/(T_\infty - T_{c,in})$

Subscripts, Accents

$\overline{()}$	laterally averaged
$\overline{\overline{()}}$	area averaged
avg	average
$c,inlet$	coolant at film cooling hole inlet
c,in	coolant upstream of impingement plate
i	internal
∞	mainstream or external
$film$	external driving temperature location
loc	local
o	impingement cooling only
s	static
tot	total
w	wall

effectiveness (ϕ), since that is the value of most interest to turbine designers. To determine the non-dimensional temperature, a conjugate experiment or simulation must use a properly scaled conjugate model that couples the convective heating and cooling and solid conduction.

As will be discussed in the following sections, recent experiments and simulations have begun to investigate conjugate heat transfer effects to provide scaled metal temperatures. This study focus on the conjugate heat transfer results due to variations in the internal impingement cooling geometry, building upon the results for a blade endwall with impingement and film cooling by Mensch et al. [1,2]. Conjugate experiments and computational simulations are used to examine the influence of internal impingement cooling geometry on wall temperatures and internal heat transfer coefficients. The convective cooling under the endwall of a turbine airfoil is of interest in this study, specifically the effects of the distance between the impingement plate and the endwall target.

2. Relevant literature

Numerous experiments with constant temperature and constant heat flux boundary conditions are found in the literature for turbine airfoils, but these studies provide only a portion of the required boundary condition information to predict the actual endwall temperature. Internal heat transfer coefficients for engine relevant geometries of internal impingement cooling can be found in the papers by Florschuetz et al. [3] and Hollworth and Dagan [4,5]. These two studies provide correlations for the Nu as functions of jet Re and geometric parameters with a constant temperature boundary condition. Florschuetz et al. [3] considered staggered impingement jet geometries where the coolant was extracted laterally from one side. The authors found that the crossflow that developed in the channel generally degraded the heat transfer coefficient from the first row of jets to the exit row. Hollworth and Dagan [4,5] measured the Nu for staggered impingement geometries where the coolant is extracted through angled holes in the target plate, which simulates a configuration with combined impingement and film cooling. Hollworth and Dagan [4] provided a correlation for the area-averaged Nu for configurations with impingement and film cooling extraction. Although some geometric parameters are included in the impingement correlations, the ratio of impingement holes to extraction holes is not included, and this ratio may differ for realistic endwall geometries such as the one presented in our study. The impingement heat transfer effects of certain parameters, such as the distance between the impingement plate and the target, H, were reviewed by Viskanta [6]. The Nu for the impingement jets usually varied with the impingement channel height to hole diameter ratio, H/D, with a maximum occurring between H/D of 1.5–4 depending on the specific jet arrangement and method of Nu measurement [3,4,6]. For impingement with film cooling extraction, Hollworth and Dagan [4] found that for the smallest spacing between impingement jets, 5D, there was not much change in Nu for a wide range of $H/D = 0.5$–6.0.

Conjugate heat transfer models to determine the overall effectiveness, ϕ, or non-dimensional wall temperature, have been applied to various geometries including flat plates, leading edge models, and full turbine airfoil models. The conjugate effects of conduction and film cooling for a flat plate were examined by Wang and Zhao [7] with a two-dimensional slot geometry. They compared the results obtained for different wall boundary conditions including adiabatic and conjugate walls. While the adiabatic wall temperatures varied across the surfaces, the scaled conducting wall temperature, ϕ, was relatively uniform. In the gas turbine industry, the conduction in the metal components is often assumed to dominate the heat transfer, smear temperature gradients, and produce nearly constant ϕ. However, even for the case of a very low Biot number, $Bi \sim 0.03$, Wang and Zhao [7] showed that ϕ varied locally and was not uniform across the surface. Conjugate heat transfer experiments for turbine applications were pioneered by Hylton et al. [8,9] and Turner et al. [10]. Although the Bi was not identified, these studies improved the understanding of the thermal fields of a conducting vane, and provided experimental data for benchmarking computational work.